슈퍼요소기법을 이용한 대규모 유한요소법의 크레인선 구조해석 적용 연구

A Study on Large Scale FEM for Structural Analysis of a Crane Vessel Using Superelement Technique

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요 약

슈퍼요소를 이용한 구조해석은 항공기나 선박 등 대형구조물의 해석에서 장점을 가지며 하드웨어의 제한된 조건속에서 효과적인 결과를 준다.

본 논문에서는 고정된 타이백(tie back) 상태에서 세계 최대의 5000톤, 회전 상태에서 3000톤을 들어 올릴 수 있는 크레인선의 구조 안전성 검토를 위하여 슈퍼요소로 분할된 부분 구조물 해석을 다루었으며, 효과적인 부분구조화(substructuring)과정과 독특한 하중추출방법 및 유한요소 모델링 기법을 제시하고 있다. 또한 해석결과에 근거한 실질적인 구조물의 총괄적 국부보강방법을 보여주고 있다.

대형 크레인선의 구조해석적용 연구를 통하여 부분구조기법의 효율성을 확립하였으며 이러한 해석기법을 통하여 새로운 형태의 유사한 구조물에 대한 해석지침을 제시하고 있다.

Abstract

Superelement technique for structural analysis of large scale objects such as airplanes or vessels is effective especially in the harsh hardware environments.

In this paper, a crane vessel of OHI 5000 which is capable of lifting 5000 tons in tie-backs and capable of revolving with 3000 tons is investigated in the view point of structural safety using superelements through the substructure scheme. Also an effective substructure procedure, a unique load extraction method and finite element modeling technique are demonstrated. Comprehensive reinforcement blueprints are derived based on the analysis results.

Successful application of substructure technique is achieved through the structural analysis of the crane vessel. The analysis technique developed in this paper can be a guideline for similar large scale structures' relevant safety identification.

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이 논문에 대한 토론을 1995년 3월 31일까지 본 학회에 보내주시면 1995년 9월호에 그 결과를 게재하겠습니다.

1. Introduction

Owned by HHI and OPS joint venture, the OHI 5000 was originally built in 1965 as a tanker and in 1976 converted to a heavy lift ship. The existing 2000t revolving crane is to be removed and replaced with a larger, AmClyde Mode 80E, capable of revolving with a 3000t load. In a fixed, over-the-bow position, with a sheer leg arrangement with tie-backs, it will be capable of lifting 5000t.

The overall goals of this work are to verify that the hull structure is basically adequate to support the new crane and rated lifting loads and to establish what reinforcements are needed. It is also the redesign of the crane tub, as it directly supports the new crane. Moreover, the goal is to establish that the hull and planned modifications are effective and sound and meet regulatory and Classification Society requirements.

In the original conversion, the tanker bow was cut off at a point 1800 forward of Frame 93 and replaced with a new bow especially designed for the crane. This part of the present OHI 5000 is well suited for the purpose of transferring load into the hull and the intent is to use this capacity and reinforce the structure only where necessary. While the new loads are substantially higher, the foundation does have available extra capacity and these efforts are directed toward demonstrating that capacity. In as much as the local loading and mechanical arrangement, the main design efforts are directed toward reconstructing the tub above the forecastle deck.

This paper addresses the design and analysis of the crane foundation.

2. Design Criteria and Loading

2.1 Design Criteria

The primary design criteria used for loading and stress levels are the American Bureau of Shipping "Guide for Certification of Cranes" (ABS Cranes)[1,2] and the Specifications provided by AmClyde(AmClyde Specs).[3] In addition, as specified by ABS Cranes, the American Institute for Steel Construction "Specification for the Design, Fabrication, and Erection of Structural Steel for Buildings" (AISC) are the primary bases for allowable stresses of the crane tub and brackets and other associated structure above the main deck.[4-6] However, all normal parts of the ship below the main deck are designed according to the ABS "Rules for Classification of Steel Vessels"(ABS Ships).[7] The AmClyde Specs subordinate to ABS Cranes, but are the bases of specific technical information related to load ratings, weight, geometry, and operating conditions.

For hull structure below the main deck, with the exclusion of upper parts of webs(tub and tansverses) the allowable stresses are followed the AISC criteria. The AISC criteria, which has a lower value for the allowable shear stress, is used for the lower tub and directly connecting webs down to the second stringer (10.24m above base line). Given the type of uncertainties with coarse mesh modeling and some concern about the age of original structure(tub and some connecting part are new in 1976), it is generally the goal of keeping the indicated shear stress less than 0.80t /cm^2(all steels of main deck and below main deck are mild).[8] Similarly, the indicated axial stress of the hull finite element model shall be less than 1.15t /cm^2.

For the upper tub, which is all new steel, all

DH36, the AISC allowable stresses are used. For the middle tub and forecastle web structure, which is all new in 1976(HT36 tub ; mild elsewhere), the AISC criteria are also used, but, due to the uncertainties of modeling, indicated stresses above 0.85 of the allowable one are to be used as a basis for reinforcement.

2.2 Crane Description and Loading

2.2.1 Crane Description

The subject crane is a AmClyde Model 80E. It is a revolving, tub mounted heavy lift crane rated at 3000t revolving. In a fixed position, lifting over-the-bow, rigged in a sheer leg mode with a special tie-back, it is rated at 5000t.

The crane is supported by 24 down bearing rollers and 8 up bearing hook rollers. The down rollers are arranged in two bogies in the form with 8 wheels each and two bogies in the rear with 4 rolls each. The hook rollers are arranged in two bogies with 4 rollers each. All bogies are fully equalized.

The given weight of the crane is 4140t. The center of weight depends on the boom position.

2.2.2 Crane Loading

Crane loading includes the lift load, the self weight of the crane, and dynamic load factors due to heel and trim. Crane loading is addressed with two perspectives :

Loading from the machine design perspective addresses failure of a machine component and includes overload factors related to that component's risk and overload considerations. It includes various loading maximums which do not apply to all positions and may not occur simultaneously, and includes special load factors unrelated to global equilibrium. This loading is used for design of the tub above the forecastle deck, particularly detail design of the top end and roller paths. It is also the basis of the crane design.

Loading form the structural perspective considers loading on a global basis, with particular emphases on global equilibrium of all forces. This loading is used for the hull structure design, primarily for structures form the forecastle deck to the hull.

2.3 Large Scale FEM Loading

2.3.1 General[9-11]

The primary purpose of the large scale FEM is to investigate the distribution of the crane loads into the crane foundation and into the hull. It is also to be used to examine associated hull stress in the forward part of the ship. As a secondary purpose, the model is extended far enough toward the end to enable it to provide supplemental information on global hull bending and torsion.

The loading conditions examined correspond to two operating conditions for the crane. One operating condition, "Rotating", considers the crane in several positions of rotation. The other operating condition, "Fixed Position", considers only one position, but has three conditions of secondary support for the crane. Table 1 defines the operating load conditions applied to the large scale FEM by load case number and its distinctions.

For completeness of loading on the global level, the large scale FEM requires consideration of buoyancy and self weight. Fig. 1 shows a schematic of the ship and the corresponding large scale FEM model. The model is cut off at Frame 78 and includes all the necessary balancing forces to produce the correct moment and shear at the cut off point. The result of stability analysis shows that the maximum bending is occured forward of Frame 81 and, for the controlling case, maximum shear is also.

In addition to hull bending from vertical plane loading, the crane side load condition exerts torsion on the hull. The torsion is nearly constant from the crane to Frame 81, at which point ballast is employed to balance the torsion. Although a minor lateral component of moment and shear is produced in the heeled condition(1.5 degree), this is inconsequential and neglected.

Table 1. Crane Load Conditions

Load Condition	Lift(t)	Angle	Comment
1-Rotating, No heel	3000	0	Forward
2-Rotating, No heel	3000	30	
3-Rotating	3000	60	
4-Rotating, 1.5 degree heel	3000	90	Side
5-Rotating	3000	120	
6-Rotating	3000	150	
7-Rotating, No heel	3000	180	Aft
8-Bow Lift, 0% Tie-Back	5000	0	
9-Bow Lift, 60% Tie-Back	5000	0	Normal
10-Bow Lift, 100% Tie-Back	5000	0	

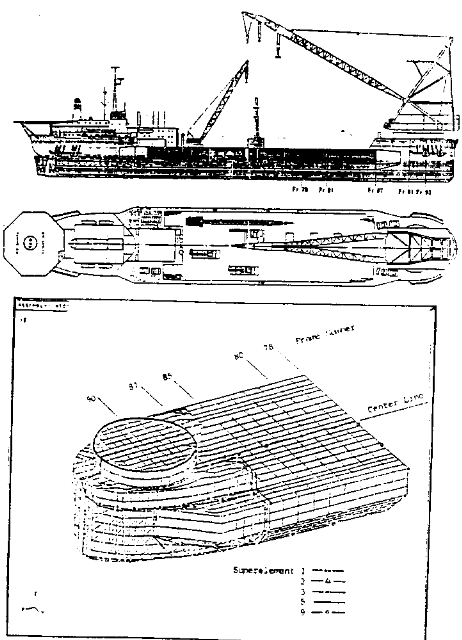


Fig. 1. The Ship and Assembled Model and superelements

2.3.2 Buoyancy and Self Weight[12]

Buoyancy

The buoyancy load was estimated on the basis of sectional areas at midship, Frame 90, and Frame 93. It was assumed that midship extends to Frame 87 and distribution between forward is linear. The basis draft used is 11m with values corrected for actual operating drafts. The final drafts of the opreating cases are 11.2m for the bow lift and 10.0m for the revolving lift. The adjustment is based upon linear scaling the sectional area of the oprating displacement to the basis draft displacement. Table 2 lists the basis buoyancy values and those for the 10.0m and 11.2m drafts.

Self Weight

The self weight is based upon the original lightship weight, known removals, and known additions to produce the new lightship weight. These weights exclude the new crane which is treated separately as crane loads on the foundation. Of an original light ship of 20,165t, 3403t is removed(mostly crane), leaving 16,762t. 80% of this is assumed to be distributed uniformly over the length of the vessel. 5% is assumed to be distributed between the FP and Frame 87. The balance is considered to be aft, consisting of deck house and machinery.

The added weights are as follows :

Crane foundation and other : 1250t FP→Fr. 87

Equipment in Hold #1 : 300t Fr.87→Fr.84

New sponson along 146m : 1940t Fr.93→Fr. 47

Table 2. Operating Condition Buoyancy Value(t)

Condition	Basis	Revolving Lift	Bow Lift
Displacement	68,290t	61,055t	70,114t
Frame	11.0m Draft	10.0m Draft	11.2m Draft
FP	0.0	0.0	0.0
93	253.2	226.4	260.0
90	350.5	313.4	359.9
87 to 56	435.0	389.0	446.6

In addition, aft of Frame 81, the appropriate ballast is included. The weight curve is given in Table 3.

Application

Specific distribution of the weight and buoyancy loading to a coarse mesh, is not especially important except it must be an edge load to a stable plane of elements(bulkhead, web, or frame). In order to produce the appropriate shear and bending in the sections of interest(forward of Frame 81), the loading must have a correct longitudinal distribution. Lateral distribution will be of some importance to the distribution near the crane foundation.

Table 3. Operating Condition Weight Value(t/ m)

Frame	Value
FP －Fr 93	125.5
Fr 93－Fr 87	138.7
Fr 87－Fr 81	68.1
Fr 91－Fr 78	303.1 : Revolving at. 10.0m draft
Fr 91－Fr 78	403.2 : Bow Lift at 11.2m draft

Table 4. Crane Wheel Loads－3000t Rotating Lift

Angle(degree)	Wheel Loadings	
	Front Wheels	Back Wheels
0 Forward	16@702t down	8@368t up
30	16@717t down	8@396t up
60	16@724t down	8@409t up
90 Side	16@731t down	8@423t up
120	16@724t down	8@409t up
150	16@717t down	8@396t up
180 Art	16@702t down	8@368t up

The weight and buoyancy load between Frame 78 and 87 is applied to the model along the center web, longitudinal bulkhead, side shell, and outer sponson shell edges according to spacing proportions.

The weight and buoyancy loading between Frame 87 and FP was initially applied as line loads along the longitudinal bulkheads and center line. However, this turned out to be too severe and obscured interpretation of the results. Subsequent reapplication of the loading was with laterally distributed line loads at each frame.

2.3.3 Crane Loading

General

The crane loads are applied to the crane tub structure as discrete wheel loads. For downward loading there are 8 wheels on each side of the front of the crane and 4 wheels on each side of the back of the crane, all on the 12, 195m radius circle. These wheels are evenly spaced. In addition, for upward load only there are 4 wheels on each side at the back of the crane, all on a 12,745m radius. These wheels are not evenly spaced. For the rotation load cases, these locations rotate relative to the vessel and crane foundation.

Table 5. Crane Wheel Loads－5000t Bow Lift

Tie-Back	Wheel Loadings	
	Front Wheels	Back Wheels
10%	16@961t down	8@779t up
60%	16@693t down	8@ 60t up
100%	16@482t down	8@969t down

Rotating Lift Conditions

Table 4 gives the wheel loadings to be used for each rotated position of the crane. The over-the-side condition at 90 degrees coresponds to a 1.5 degree list. The over-the-bow and stern conditions at the 0 and 180 degrees correspond to no list. Because the list is not specifically known between these angles, the wheel loads are interpolated, thus approximating some list.

These wheel loads do not include crane side load because of directional ambiguity. While not particularly important on the global level and with respect to load distribution into the hull, this omission must be considered when considering stress values above the main deck. All other load factors are included, particularly the 10% load factor appiled to the lift load.

Bow Lift Conditions

Table 5 gives the wheel loadings to be used for esch tie-back tension. The positions of these wheel loads are the same as those applied.

Application

To facilitate application of the loading to the FEM, a special superelement is prepared for the model to carry the loads. SESAM system[13] developed by VSS is employed for the analysis. Necessary sub-programs for systematic application of the code are developed. Interactive preprocessors and postprocessors are also used.

For typical similar 3−D frame analysis, 4000−6000 sec. CPU and 3−4 hours of run time is needed using SUN system, however for the present model it is impossible to run with limited hard disk space. SUN 386i /250 of 8MB RAM, 5MIPS, 327 MB HDD, 3.5″ HD is used for the analysis with superelements. For the analysis, it takes 8−10 hours with this SUN computer.

3. Structural Simulation

3.1 General[9-10]

The structure is divided to substructures and the stiffness equation is written in partitioned form, separtating contributions of points on the boundary of substructures from points interior to the substructures.

In the displacement method each substructure is first analyzed separately, assuming that all common boundaries with the adjacent substructures are completely fixed ; these boudnaries are then relaxed simultaneously, and the actual boundary displacements are determined from the equations of equlibrium of forces at the boundary joints. Naturally, the solution for the boundary displacements involves a considerably smaller number of unknowns compared with the solution for the complete structure without partitioning. Each substructure can then be analyzed separately under known substructure loading and boundary displacements. This can be done without difficulty since the matrices involved are of a relatively small size.

The complete set of equilibrium equations for the structure may be written in matrix form as

$$KU = F$$

The total stiffness matrix can be written in partitioned form as

$$K=\begin{bmatrix} K_{bb} & K_{bi} \\ K_{ib} & K_{ii} \end{bmatrix}$$

where the subscripts b and i on the matrix partitions refers to terms for the boundary part and interior part, respectively.

After further manipulations, the boundary stiffness matrix can be represented as the following form

$$\overline{K}=K_{bb}-K_{bi}\cdot K_{ii}^{-1}\cdot K_{ib}$$

The corresponding forces can be represented as the following form

$$\overline{F}=F_b-K_{bi}\,K_{ii}^{-1}\,F_i$$

The computational procedure based on the altered stiffness and nodal loads outlined above is applied.

Coarse mesh Finite Element Model(FEM) is prepared to check the strength of tub foundation and midship structure, at the beginning.

Modelling is extended to Frame 78 to reduce the boundary effects on the crane foundation and to check the longitudinal and transverse strength around Frame 81. (Stability analysis shows that maximum bending moment happens around Frame 81.) In this case, however, there may be significant troubles in hard disk space and CPU time due to the increase number of elements and nodes. To overcome this problem, substructuring technique is used. The substructuring scheme and details of each superelement are described in the following sections.

The general scheme of modelling is as follows :

- Modelling of each superelement is prepared for the port structure only assuming the structure is symmetric about center line.
- Membrane and truss elements are used because in-plane stresses due to crane load is the major concern of this analysis.
- Modelling range is from Frame 78 to 96.
- The flare and bow details are simplified.
- Tub and tub supporting model includes vertical stiffeners to check the effect of vertical load reasonably. This model, however, does not include longitudinal stiffeners.
- The model between Frame 78 and 87 includes longitudinal stiffeners to check the longitudinal strength reasonably.
- Corrugated bulkheads are simulated by orthotropic element. The axial stiddness to the strong axis and shear stiffness are increased by the ratio of section area and the axial stiffness to the weak axis is assumed to be very small, i.e., 0.1% of that to the strong axis, to avoid singularity.
- Openings for the hatch, bow thruster, moon pool, or mooring line are neglected in the modelling.

3.2 Total Model

Total structure is assembled from five basic superelements(see Fig. 1) to reduce CPU time and disk space.[14] All superelements except Superelement 5 represent corresponding port side structures because of the symmetry of ship.

Superelement No.

1 : Tub supporting model under main deck between Frame 87 and 96.
2 : Bow sponson model between Frame 87 and 93.
3 : Tub model above main deck.
5 : Crane load model
9 : Midship model between Frame 78 and 87.

3.3 Boundary Condition

All displacement components on the Frame 78 are constrained.

4. Analysis Results & Discussions

Structural analysis was performed for normal and redundant operating conditions under the load calculated considering global equilibrium.

The typical deformed shapes for bow lifting and side lifting are shown from Fig. 2 to 4. Fig. 2 shows that there is rapid increase of vertical displacement at the forward of Frame 87. It is due to the difference of modelling scheme, i.e., Midship Model(Superelement 9) includes longitudinal stiffeners to check longitudinal strength and Tub Support Model (Superelement 1) and Bow Sponson Model (Superelement 2) do not include them. So the maximum vertical displacement, −16.5cm, is somewhat conservative.

The result shows high stresses at many ver-

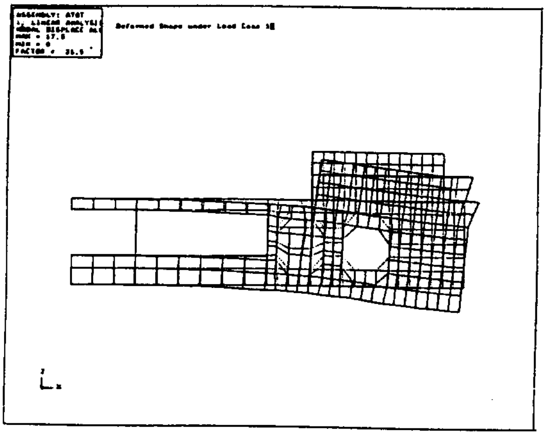


Fig. 2. Deformed Shape of Center Bulkhead and Web under Bow Lifting

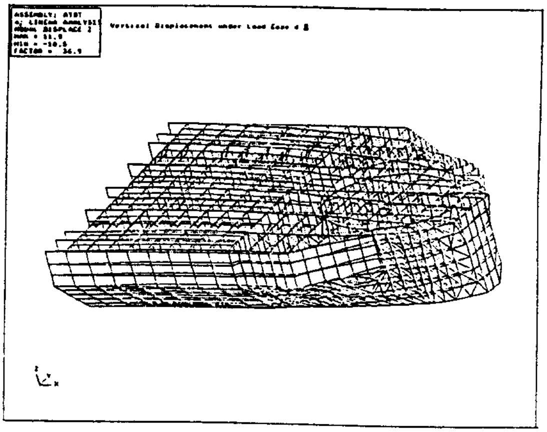


Fig. 3. Vertical Deformation under Side Lifting

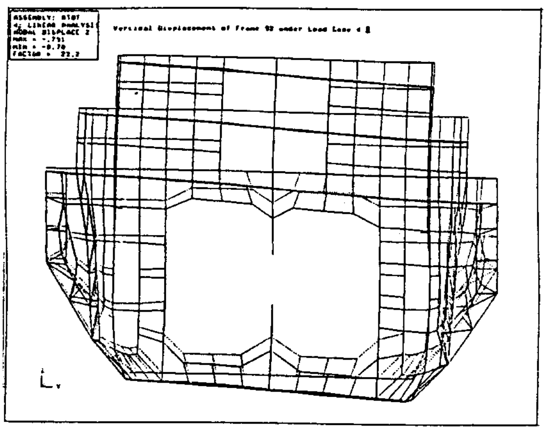


Fig. 4. Vertical Deformation of Frame 92 under Side Lifting

tical members. So many reinforcements are required to uprate the crane capacity. The typical reinforcement items are as follows(see Fig. 5) :[15-16)]

- Reinforcement Item 1 : Fill the opening and reduce the size of shaft hole in the center bulkhead and web.
- Reinforcement Item 2 : Arrange stiffeners under the tip of tub bracket and modify shape of opening on the transverse web to distribute vertical force along longer length and to distribute it to strong structure such as side shell or sponson.
- Reinforcement Item 3 : Extend longitudinal bulkhead to the forecastle deck between Frame 90 and 94.
- Reinforcement Item 4 : Reduce the size of opening around deep bracket.
- Reinforcement Item 5 : Reinforce the intersection part between web plate and longitudinal corrugated bulkhead to resist vertical force.

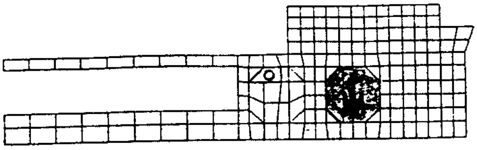
The details of the above reinforcement scheme will be decided during the design and analysis of the crance foundation.

Special attention is required to control tie back force because longitudinal stress exceeds allowable value at redundancy conditions, 0% and 100% tie back.

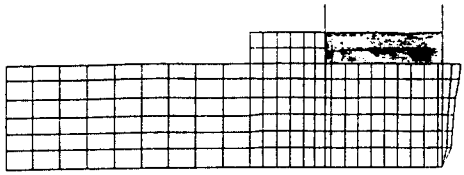
5. Conclusions

Large scale FEM for successful structural analysis of a crane vessel is demonstrated by employing the superelement technique. The technique is proven to be effective especially for the problem. Without the implementation of the substructuring, the analysis would not have be done since the matrices involved are of a conciderably huge.

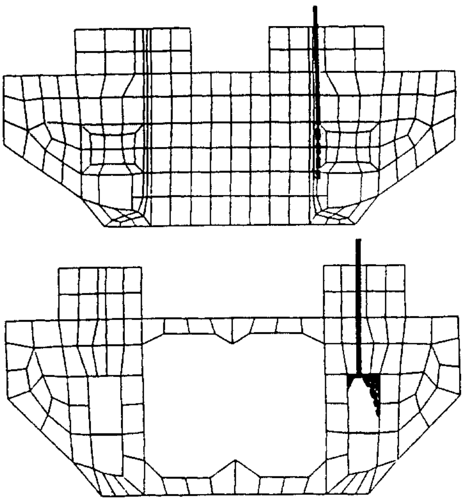
Comprehensive reinforcement scheme is de-



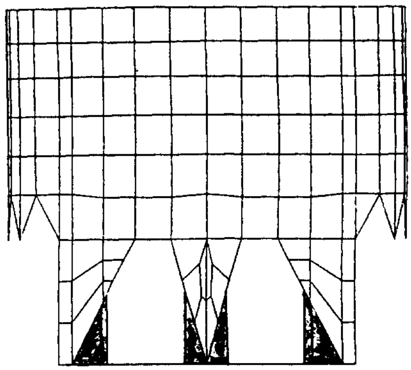
Reinforcement Item 1 : Fill the opening and reduce the size of shaft hole in the center bulkhead and web.



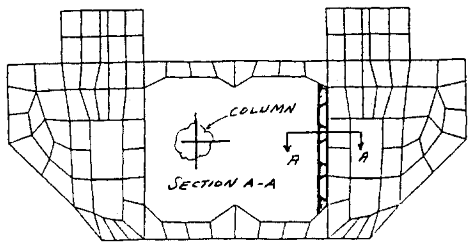
Reinforcement Item 3 : Extend longitudinal bulkhead to the forecastle deck between Frame 90 and 94.



Reinforcement Item 2 : Arrange stiffeners under the tip of tub bracket and modify shape of opening on the transverse web to distribute vertical force along longer length and to distribute it to strong structure such as side shell and sponson.



Reinforcement Item 4 : Reduce the size of opening around deep bracket.



Reinforcement Item 5 : Reinforce the intersection part between web plate and longitudinal corrugated bulkhead for it to behave like a column.

Fig. 5. Reinforcement Scheme

rived for the uprate of 5000t crane vessel through the work. The scheme is proved to be very useful for the redesign of the ship resulting from the discussion with the authority concerned such as ABS. The application of the modification approach used in the redesign the OHI 5000 can be basis for similar crane vessel modification.

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